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A special kind of local structure in the CMB intensity maps: duel peak structure *

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Abstract We study the local structure of Cosmic Microwave Background (CMB) temperature maps released by the Wilkinson Microwave Anisotropy Probe (WMAP) team, and find a new kind of structure, which can be described as follows: a peak (or valley) of average temperature is often followed by a peak of temperature fluctuation that is 4° away. This structure is important for the following reasons: both the well known cold spot detected by Cruz et al. and the hot spot detected by Vielva et al. with the same technology (the third spot in their article) have such structure; more spots that are similar to them can be found on CMB maps and they also tend to be significant cold/hot spots; if we change the 4° characteristic into an artificial one, such as 3° or 5°, there will be less "similar spots", and the temperature peaks or valleys will be less significant. The presented "similar spots" have passed a strict consistency test which requires them to be significant on at least three different CMB temperature maps. We hope that this article could arouse some interest in the relationship of average temperature with temperature fluctuation in local areas; meanwhile, we are also trying to find an explanation for it which might be important to CMB observation and theory.

Key words: cosmic microwave background — cosmology: observations — methods: data analysis

1 INTRODUCTION

The local structure of the CMB is very important since research about it can often influence the study of asymmetry, non-Gaussian signatures, etc. For instance, hot and cold spot analysis (Larson & Wandelt 2004, 2005), local curvature methods (Hansen et al. 2004; Cabella et al. 2005), local power spectra (Hansen et al. 2004a) and wavelet space analysis (Vielva et al. 2004, 2007; Mukherjee & Wang 2004; Cruz et al. 2005, 2006; McEwen et al. 2005, 2008; Cay'on, Jin & Treaster 2005; Liu & Zhang 2005). However, little work has been done on the relationship between two properties - average temperature and temperature fluctuation - in the same local area. This article is such an attempt. We organize pixels near a certain spot by their angular distances to it, and compute those two statistical properties at different

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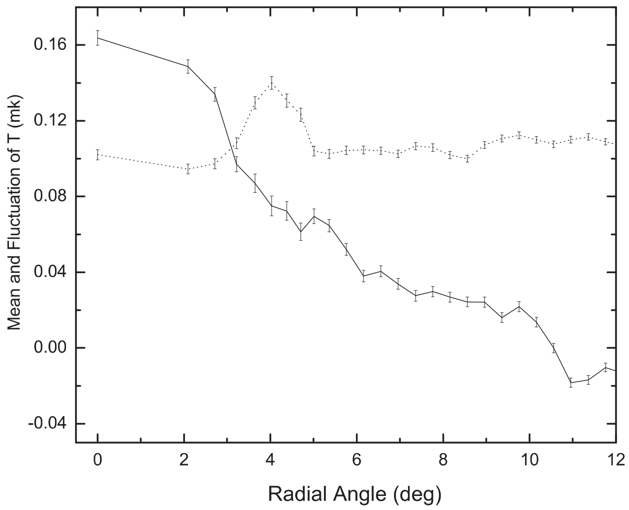

Fig. 1 Curves of a position centered at $(b, l) = (-55.8, 209.4)$, which is very close to the well known cold spot. The input data is TOH map. The dotted curve stands for temperature fluctuation (v_i) and the solid curve for average temperature (u_i) (the original average temperatures are mostly negative; however, since the fluctuation is always positive, we decide to plot the reversed average temperature here to reduce the figure size). The horizontal unit is degree and the vertical unit is mK.

angular distances; in this way, we present a direct representation of the structure of this area from which we derive the new duel peak structure. The following sections are organized in this way: Section 2 introduces our method for describing the local structures; Section 3 shows how to find similar spots all over the sky and gives corresponding results; Section 4 derives this new type of structure from given instances and tests it in 3° and 5° cases; in the end, we give our conclusions and the goal of future work in Section 5.

2 OUR METHOD FOR DESCRIBING LOCAL STRUCTURES

To study the structure of a certain position, e.g., near spot A, we define several samples which are called A_i ($i = 0, 1, 2, \ldots$). A_i contains all the spots whose radial distance to A is in the range $r_i \sim r_{i+1}$, where $r_i = 0.03\,\mathrm{rad}\times\sqrt{i}$. It is easy to see that each A_i is actually a ring around A, except for A_0, which is a disc. For each A_i, we compute its average temperature $u_i = |\langle T\rangle|$, temperature fluctuation $v_i = \sqrt{\langle(T - \langle T\rangle)^2\rangle}$ and record the average radial position for each ring as $p_i = (r_i + r_{i+1})/2$. However, since A_0 is actually a disc, we set p_0 to zero. After that, we plot two curves whose Y-axis are u_i and v_i, respectively, while the X-axis shows both p_i, as shown in Figure 1, which gives us a basic image of the duel-peak structure.

We should notice that foreground emission may affect our results, thus we must apply the KP0 galactic mask (see Bennett et al. 2003 for the definition of this mask) to the input map to exclude pixels with high foreground emission. However, in this way, one or more rings might be completely or partially covered by the KP0 mask. Our treatment is as follows: any ring from position “A” must not be covered by more than a half, otherwise we will treat this position as “unusable”. To reduce computational time, we pick the center spot using lower resolution: Healpix resolution 8 (Please see Gorski et al. 2005 for the definition of “Healpix resolution”).

3 SEARCH FOR MORE INSTANCES BY CORRELATION, PEAK SIGNIFICANCE ANALYSIS AND MULTI-FREQUENCY ANTITHESES

Figure 1 shows a peak of average temperature at $x = 0^\circ$ and a peak of temperature fluctuation at $x \approx 4^\circ$. This spot is very close to the well known cold spot and this structure is clear and impressive; moreover, our later result shows that the third hot spot discovered in Vielva et al. (2007) with the same technology also has similar structure. Therefore, we want to know if there are more spots with such a structure. This requires joint work that involves correlation analysis, peak significance analysis and a filtering step, as follows:

We use the correlation function between the curves in Figure 1 and curves from other spots to describe the similarity between them. The standard formula for the correlation function is: $R_{x,y} = \sum_i (x_i - \overline{x})(y_i - \overline{y})/(n-1)S_x S_y$; therefore, if the curves in Figure 1 are denoted by U (for u_i) and V (for v_i), while curves from other pixels are denoted by U_1 and V_1, the joint correlation function is going to be $C = |R_{U,U_1}| + |R_{V,V_1}|$. This value is computed for all the spots at resolution 8.

In addition, we should test the significance of the peaks at 4° in the fluctuation curves. Therefore, we look for the highest point "P" on curve of temperature fluctuation, and delete all nearby points including the peak, then, we apply a least square linear fit to the remaining points on this curve and extrapolate the fit value at "P". The fit values of the remaining points are called F_r, and the fit value of "P" is called F_p. Meanwhile, the original values of the remaining points are called O_r, and the original value of "P" is called O_p. With these preparations, we can derive the peak significance value as: $K = (O_p - F_p)/\sqrt{\langle (O_r - F_r)^2 \rangle}$. This value is also used for computing all the spots at resolution 8.

When correlation analysis and peak significance analysis are finished, we take out 54 spots with the highest C value from the correlation analysis' result (if one pixel is chosen, all other pixels within 0.1 rad range are discarded). Then, we start three rounds of filtering, in which correlation value, center temperature (the first value of each average temperature curve) and peak significance are used in sequence. In each round, 1/3 of the spots with the lowest value for this round are rejected (e.g., 1/3 of the spots with the lowest C are rejected in round 1). This results in 16 remaining spots for each map after three rounds, or 80 spots from all five maps. All these spots are plotted on an empty map as small discs whose radii are equal to 0.05 rad; therefore, adjacent spots will overlay each other and produce higher ones. In this way, the consistent spots for more than one map can be easily recorded.

We do these things on five CMB maps including the TOH temperature map (Termark et al. 2003), the WMAP three year ILC map (Bennett et al. 2003) and the WMAP three year combined foreground clean maps of Q, V and W bands (Hinshaw et al. 2007). These five maps have different noise properties, foregrounds and beam functions (especially for Q, V and W band maps); therefore, a consistent spot for

Table 1 Consistent Spots Derived from the Five Maps' Results

No.	b in (b, l)	l in (b, l)	maps
1	–55.8	209.4	all
2	–85.1	113.4	all
3	–31.1	318.1	1, 4
4	58.3	55.5	1, 3, 4, 5
5	76.9	155.8	1, 2, 5
6	28.7	83.1	1, 3, 4
7	27.2	224.0	1, 2, 4
8	–27.7	159.2	1, 4, 5
9	–44.4	20.2	1, 3, 5
10	–65.7	225.9	1, 3, 5
11	–32.2	325.3	2, 3, 5
12	–38.1	132.6	2, 3, 5

This table contains information about the 12 consistent spots including their positions and in which maps they are significant (the number '1, 2, 3, 4 and 5' in 'maps' row stand in sequence for TOH, ILC, Q, V, W maps).

all or most of these five maps must contain fewer non-CMB effects and should be much more reliable. The consistent spots derived from the five maps' results are listed in Table 1, and their curves are given in Figure 2. The error bars in Figure 2 show that our results are not affected much by noise. In the end, we perform a manual check on all these consistent spots for the following reason: automatic search is not 100% accurate; it rarely misses a "wanted" spot, but it sometimes accepts unwanted spots, which must be excluded manually. According to Figure 2, we decide that spots 2, 4, 6, 7 and 12 should be excluded. The reasons why they should be excluded are given right after Figure 2.

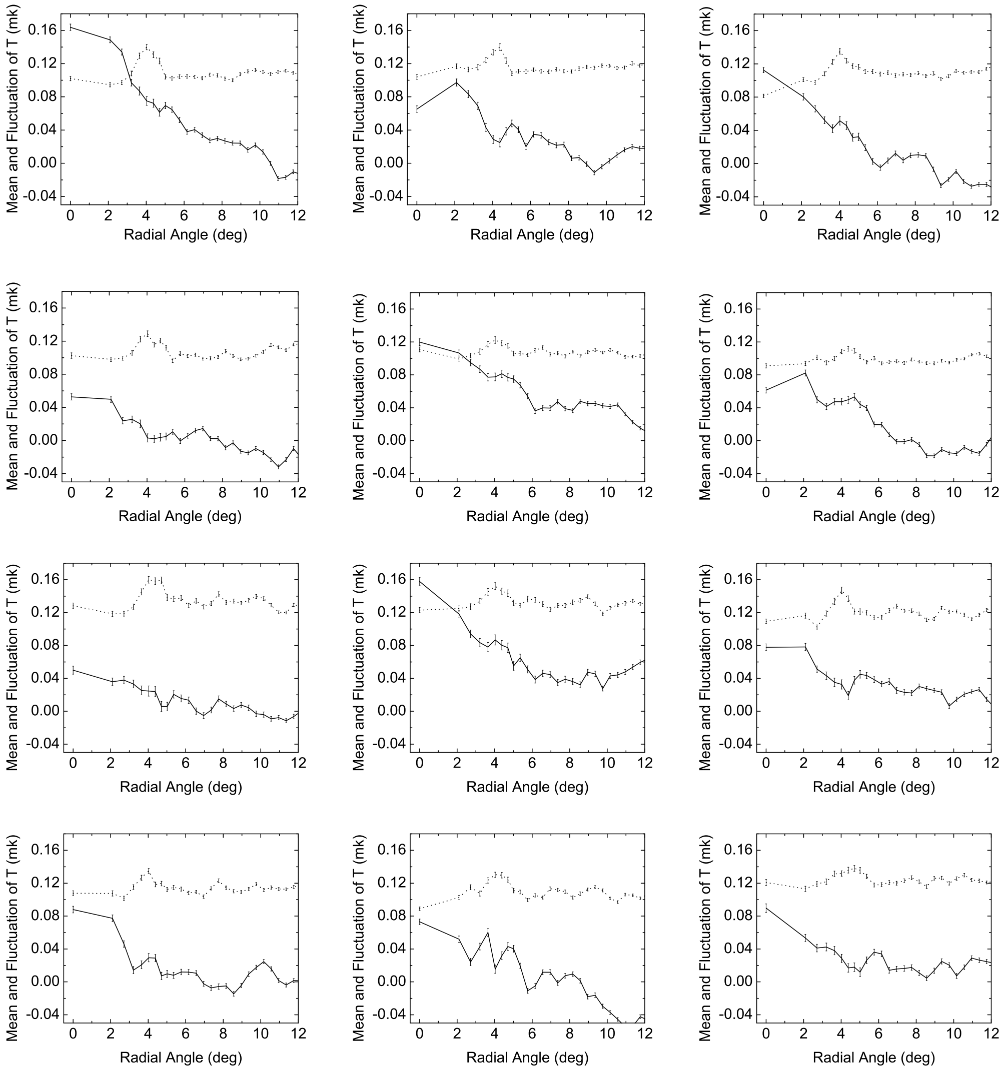

Fig. 2 Curves of 12 spots that are significant in at least 3 maps' results. From top to bottom: 1–3, 4–6, 7–9, 10–12. The units and meanings of different lines are the same as Fig. 1. The average temperature of 1, 4, 6, 8, 12 are reversed to make the curve positive. The input is TOH map. As mentioned in section 3, here are the reasons why spots 2, 4, 6, 7, 12 should be excluded. Spot 2: the temperature peak is not at the center; spot 4: the center temperature is too low; spot 6: same as spot 2; spot 7: same as spot 4; spot 12: the peak of the temperature fluctuation is not at the 4-degree position.

Among the remaining spots, we should notice that spot 1 is very close to the well known cold spot, and spots 3 and 11 are very close to the third hot spot reported by Vielva et al. (2007). Since spot 3 and spot 11 are also very close to each other, if they were considered to be one spot, this spot would appear on each of those five maps; therefore, we choose to treat them as one spot.

4 SIGNIFICANCE OF THE CHARACTERISTIC "FOUR-DEGREES"

We have found a new type of duel-peak structure which can be summarized as "Peak (valley) of average temperature accompanied by peak of temperature fluctuation that is $4°$ away." The most important characteristic of this structure is the $4°$ radial distance, which can be verified by changing it into $3°$ and $5°$, respectively. We shift the entire temperature fluctuation curve in Figure 1 by $1°$ left or right recursively to produce a $3°$ or $5°$ curve, and then repeated the entire process to see if any consistent spots could be found. The result for the $3°$ case was ten consistent spots, eight excluded for similar reasons as in Figure 2 and the average center temperature for the remaining two spots is 0.068 mK. Meanwhile, the $5°$ case resulted in another ten consistent spots, five excluded, and the remaining five spots' center temperatures average at 0.076 mK; in contrast, in the $4°$ case, there are twelve consistent spots, five excluded, and the five highest center temperature averages of 0.111 mK, about 64% higher than the $3°$ case and about 46% higher than the $5°$ case. Therefore, we are confident that the $4°$ structure is really significant. Besides, we can see that this structure tends to appear in significant cold/hot spots; this might be important in explaining it.

5 CONCLUSIONS

We have found a new type of structure in CMB maps with seven consistent and manually checked instances, including the well known cold spot and the third hot spot from Cruz et al. (2005) and Vielva et al. (2007). It seems that the well known cold spot is not alone, and the reason that makes it outstanding might have something to do with the joined effect of average temperature and temperature fluctuation. The characteristic radial distance of $4°$ should also be noticed. We are still trying to find the reason for such a kind of structure, and we believe that a reasonable explanation might help to improve the theory of cosmology.

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